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Study on Short-term Variability of Ship Responses in Waves

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Abstract

Short-term variability of ship responses is investigated from the view point of cross-spectrum analysis. In a steady state condition, it is well known that a certain length of sampled data are required for stable spectral analysis. However, the phase angle of the cross-spectra has not been discussed in detail. Using long stationary time histories, the transition of amplitudes and relative phase angles of the cross-spectra have been investigated by iterative analyzes with a few seconds of time shifting. In the results, the short-term variability of the relative phase angle was observed. This concludes that the variability influences the accuracy of the wave buoy analogy.

Keywords: Ship handling and propulsion, wave buoy analogy, aleatory uncertainty, Fourier transform, relative phase.

1. Introduction

The authors of the present paper are advocates of the wave buoy analogy. In this analogy, measured responses from an advancing ship are used together with corresponding transfer functions to obtain estimates of the sea state at the exact position of the ship [(1), (2), (3)]. In general, results of the wave buoy analogy compare reasonably well with results of other means for wave estimation [(4),(5)] but observations with poor agreement are also found; not to mention which means are the most accurate. This brings into question how much variation, due to aleatory uncertainty [(6)], the sea state itself may exhibit on a short-term scale in 2-5 minutes period.

A direct measure for the aleatory short-term variation of a sea state in time and position could be obtained on the basis of results by the wave buoy analogy. However, an indirect approach is to estimate the sea state variation in terms of measured ship responses, since any change in sea state will be observable in the wave-induced responses of a ship; assuming other operational parameters (speed, heading, etc.) to be constant and neglecting the fact that a ship, to some degree, is a wave filter. The advantage by this indirect approach is that modelling uncertainties, of the wave buoy analogy or other similar means for wave measurement, will not influence results. In case of the wave buoy analogy, notably uncertainty related to the transfer functions of the ship could influence results. 'Modelling uncertainties' may, in this sense, be viewed as a kind of epistemic uncertainty [(6)].

In this study, full-scale response measured by a training ship was analyzed by the ordinary Fourier transform technique, with the purpose to examine any short-term variation in the data. The responses were investigated by iterative cross-spectral analysis with a short time shifting. The transition of amplitudes and relative phase angles of the cross-spectra were monitored precisely and some uncertainties were observed. The short-term variability of the relative phase angle is illustrated and the problems that were encountered are reported.

2. Full Scale Ship Experiment

The full scale ship experiment was carried out on October 17th 2013 using the training ship Shioji-maru of Tokyo University of Marine Science and Technology. A photo and principal particulars of the ship are shown in Figure 1 and Table 1. The location of the experimental area was off Sunosaki cape in Chiba Prefecture, Japan. Ship motions and the position were measured using a fiber optic gyro and a GPS system. These data was sampled every 0.1s and recorded in the hard disk of a notebook PC through the RS-232C port.

Figure 2 shows the trajectory of the T.S. Shioji-maru during the experiment. In order to measure changes in ship motions with respect to the encounter angle of waves, the angle of CPP was set to 15 degrees. Measurement was carried out for 60 minutes involving three straight sections and changes in course. The sections A and B have 10 minutes duration and the section C has 20 minutes duration. The wave direction was SE as reported by Japan Meteorological Agency.

Table 1 Principal particulars of T.S. Shioji-maru

Length (P.P.)	46.00(m)
Breadth (M_{LD})	10.00(m)
Depth (M_{LD})	6.10(m)
Draught (M_{LD})	2.65(m)
Displacement	659.4(t)
Main engine	4 cycle diesel 1,030 kw × 700 rpm

Figure 1 The training ship Shioji-maru.

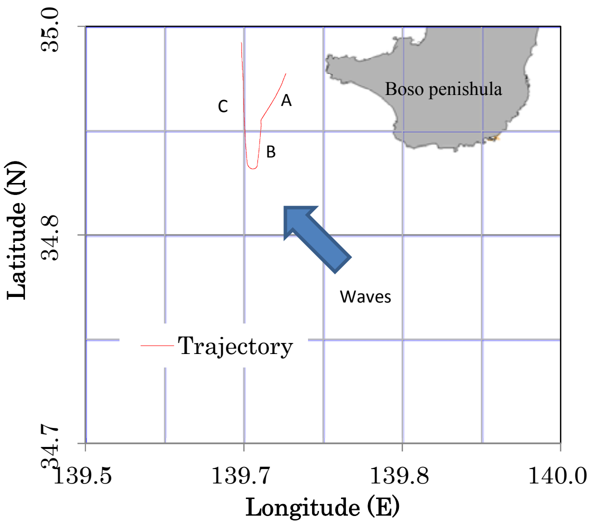

Figure 2 The experimental area at off Sunosaki cape and the ship trajectory.

Table 2 Ship course and the sea conditions

Run	Ship course (deg)	Ship speed (knot)	Duration (min)	Wind dir.	Wind speed (m/s)
A	200	11.0	10	NNE	3.0
B	180	11.0	10	NNE	3.0
C	0	10.5	20	NNE	5.0

Table 2 shows the ship courses and the mean speeds-through-water, measurement duration and true wind directions and the speeds are also summarized. During the experiment, the observed wind waves were: height 1.0-1.5m, directions 150-160 and 335-350 degrees.

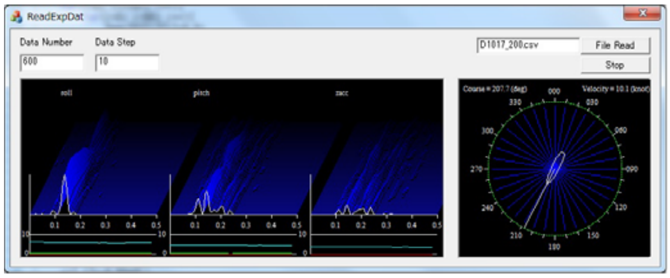

Figure 3 Screen shot of the developed software (run A).

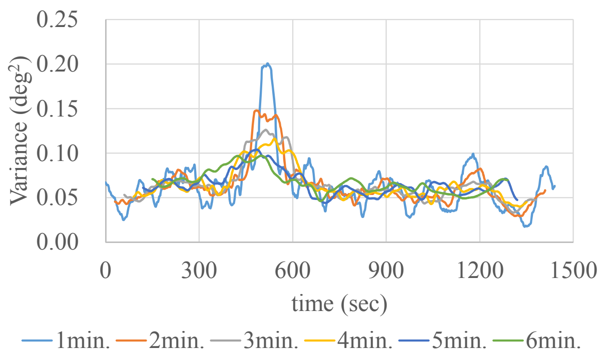

Figure 4 Transition of the pitching variance for each time spans (run C).

3. Auto-spectral analysis and the results

The computer software, which can continuously estimate auto and cross-spectra with shifting data points, has been developed for this research work. The screenshot of the software is shown in Figure 3. In the right part of the screen, the ship course and the speed are indicated and the three component of the power spectra are shown in the left part of the dialog box. The latest spectra are plotted by white color and the past spectra are drawn by blue color. In this example, the 600 data points of time histories are analyzed by Fourier transform with tapered cosine bell type data window and the analysis was iterated with 1s (10 data points) time shifting. It can be seen that the shape of spectra change smoothly with rather short period. This concludes that the 600 data points are not sufficient for analyzing the time histories.

Figure 4 shows the transition of the pitching variances that were calculated as the area of pitching auto-spectra. The data was measured on the "run C" and the data points are 15000 (25 minutes). The horizontal axis denotes the shifted time in second. There are 6 colored lines in the graph and they are indicating the time span for the Fourier transform. Therefore, the blue colored "1 min." line denotes the result evaluated by the shortest (1 minute) time span (600 data points) and is the longest line in the graph. On the contrary, the green colored “6 min” line denotes the result evaluated by the longest (6 minutes) time span (3600 data points) and is the shortest line in the graph. It can be seen that there are some large amplitude of pitching motions around 500 second and the longer time span gives the smoother result.

Figure 5 shows the transition of the mean period T_{01} of the pitching motion. In this result, the periods were calculated by dividing the spectral area (0^{th} order moment) by the 1^{st} order moment. In other words, the mean period T_{01} indicating the center of the spectral area. Therefore, the transition of the mean period means the frequency shift of the spectrum. Same as figure 4, it can be seen that the longer time span gives the smoother result. From this figure, the encounter period of the waves is around 10 seconds and 5 minutes time span must be required at least.

4. Cross-spectral analysis and the results

In general, a cross-spectrum takes complex numbers that are indicating the composite amplitude and the relative phase angle of the measurements. In this study, cross-spectra of the rolling-pitching and pitching-vertical acceleration (v.acc) were investigated by the similar method described in the previous section.

Figure 6 and 7 show the transition of the rolling-pitching and pitching-v.acc variances that were calculated as the amplitude of the cross-spectra. The shape of the transitions are almost the same as Figure 4. This concludes that there is no big difference in the influence of the time span between auto-spectra and cross spectra.

Figure 8 and 9 show the transition of the relative phase angle of rolling-pitching and pitching-v.acc. The relative phase angle can be defined at each frequency. Therefore, we defined the phase difference using the relative phase angles before and after time shifting first. Secondly, the standard deviations were calculated by the phase difference at each frequency. The standard deviation takes rather large value when the cross-spectrum has low power. The low power is calculated from weak signals and may have much phase error. In the actual calculations, therefore, the amplitude of the cross-spectra at each frequency was considered as a weighting coefficient to avoid the mixture. Comparing to

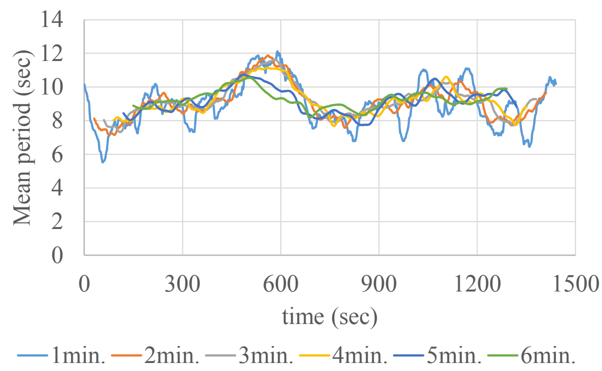

Figure 5 Transition of the mean period of pitching motion for each time span (run C).

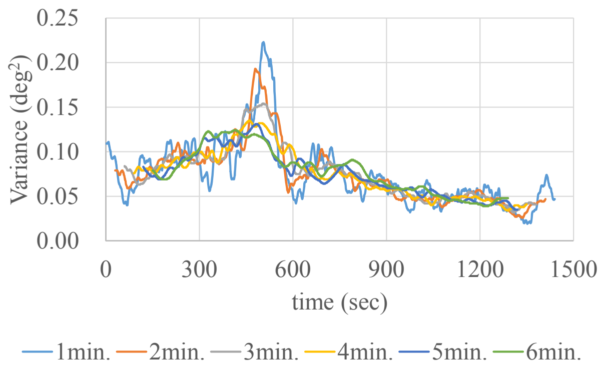

Figure 6 Transition of the amplitudes of roll –pitch cross-spectra for each time span (run C).

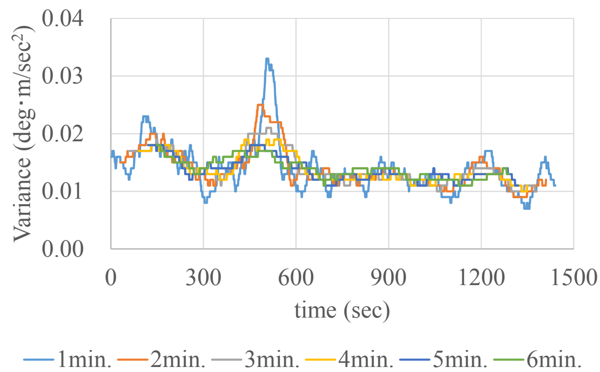

Figure 7 Transition of the amplitude of pitch-v.acc cross-spectra for each time span (run C).

the previous figures, completely different characteristics canbe seen. The standard deviations are fluctuating roughly and no periodic transition can be seen. The fluctuation can be considered as the short-term variability of the relative phase angle. In fact, the standard deviation at the large amplitude is very small but the total value over the whole frequencies takes large value. The relative phase angle of the cross-spectra involves directional information of the waves because

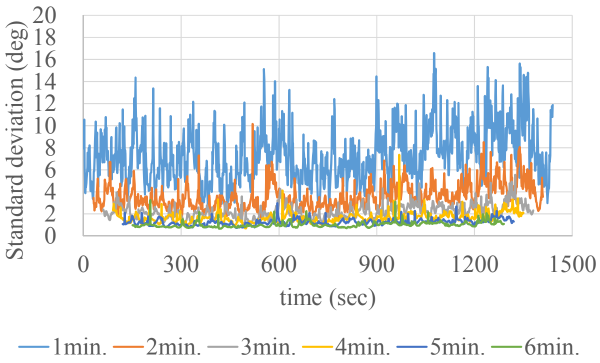

Figure 8 Transition of the phase angle of roll-pitch cross-spectra for each time span (course 0deg).

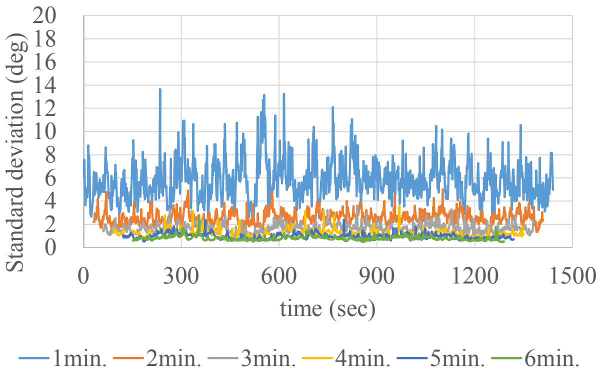

Figure 9 Transition of the phase angle of pitch-v.acc cross-spectra for each time span (course 0deg).

the ship motions are induced with a certain phase lag by the waves. Therefore, short-term variability of the relative phase angle is very harmful to the wave buoy analogy.

5. Conclusions

In this study, short-term variability of ship responses is investigated from the view point of cross-spectrum analysis. Using long stationary time histories measured by a training ship, the transition of amplitudes and relative phase angles of the cross-spectra have been investigated precisely with a few seconds of time shifting. The results obtained in this report are summarized below:

- Common sense of the spectral analysis, the longer time span the smoother result, was confirmed by the analysis of the variance of spectra.
- The short-term variability of the relative phase angle was observed and the tendency is completely different to that of the variance.
- The short-term variability of the relative phase angle is very harmful to the wave buoy analogy. The characteristics should be investigated more precisely.

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